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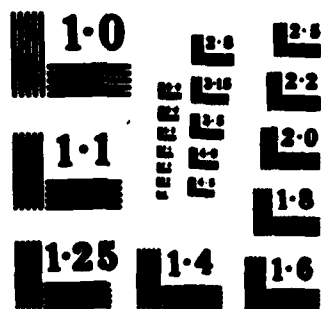
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Final Report to Office of Naval Research
on
Integrated Digital Networks
ONR Grant N00014-82-K-0508

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Introduction

This final report on ONR grant N00014-82-K-0508, on Integrated Digital Networks, summarizes the work carried out during the two years of the grant, September 1, 1982 through September 30, 1984. It covers seven areas, listed separately under individual headings in the section following.

The basic problem is that of transmitting mixtures of traffic of disparate types over a variety of communication networks. Typical examples include the transmission of interactive data, long streams of data (e.g., file transfers), voice, video, and facsimile in an integrated fashion. Network types include local area networks, metropolitan area networks, large geographically-dispersed terrestrial networks, and satellite networks. Ongoing standards work in the CCITT, supported by telephone administrations worldwide, has focused on the concept of Integrated Services Digital Networks (ISDN) toward which worldwide telecommunications will be moving. Computer manufacturers with a great deal of interest in communications (IBM is a prominent example) have begun to devote considerable effort as well to the concept of traffic integration over networks.

In keeping with this worldwide interest on the operational level, our group at Columbia began a number of years ago to look into some of the basic questions involving integration. A Ph.D. dissertation completed in 1979 was among the first to carry out analytical studies in problems of integration [1]. One of the key findings of this dissertation was that the so-called "movable boundary" strategy for combining voice (blocked traffic) and data (queued traffic) at a common time division multiplexing point was close to optimum. Two journal papers and a Conference paper have appeared, based on this work. [2-4]

This early work led to the intensive study of the area of integration in networks by our group. A summary of the work done follows.

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Summary of Work

1. Hybrid Multiplexing

Work was begun on hybrid multiplexing. This is a generalization of the earlier dissertation work on integration, referred to above. It compares different multiplexing strategies at an integrated node for multibandwidth circuit-switched and packet-switched traffic. A variety of access control strategies for blocked, queued, and combined blocked/queued traffic have been studied, and results have been obtained for some novel multiserver queueing models. This work has been presented at a number of Conferences, and a paper has been submitted for publication. [5-8]. A Ph.D. dissertation on this work was completed June 1984.

Related work on optimal policies for serving heterogeneous mixes of circuit-switched users on an integrated link was also completed under this grant. This work arose out of studies of integration of traffic on satellite-switched multiple beam systems. (Further discussion of work on satellite systems appears later in this section). A paper describing this work on integration was presented at a conference [9].

2. Time-constrained communications over local area networks.

Packetized voice serves as one notable application of this area of investigation. A variety of distributed window control mechanisms have been analyzed for their relative performance in the random access local area environment. Most recently, using some of the tools of micro-economics in studying a competitive market environment, distributed priority control disciplines have been studied as well. A dissertation on this work has just been completed. Two conference papers based on this work have been presented, and a journal paper has been published [10-12].

3. Routing of voice and data in integrated networks.

Studies have been initiated of non-hierarchical routing in circuit-switched networks, using an average end-to-end blocking probability constraint. The area of non-hierarchical routing in circuit-switched networks is a comparatively new one, most routing in the current telephone plant being carried out on a hierarchical basis. We have studied both centralized and decentralized methods of carrying out non-hierarchical routing, and have, most recently, compared non-hierarchical routing to alternate path routing, a common procedure in telephone circuit-switched routing. Our findings indicate that alternate path routing performs better for lightly-loaded networks, while non-hierarchical routing provides better performance at higher loads. This leads to the interesting possibility of using adaptive routing control, and a number of control mechanisms have been compared. A Ph.D. dissertation in this area is almost completed.

4. Integrated Services Satellite Communications

Three projects were completed in this area. The first concerned systems in which broadcast satellites are used for integrated packet and circuit switching in a time division multiple access (TDMA) mode, with time slot assignments made on a combined fixed and demand basis. The objective was to design a protocol which gives the best delay-vs.-throughput performance for packets, subject to acceptable circuit blocking probability. Using a Markovian model of the system its behavior was analyzed to obtain complete information on packet delay statistics. A control scheme was proposed to achieve optimal performance, where the optimality criterion was based on the mean and variance of packet delay. The research has been submitted for publication and is the subject of a recent doctoral dissertation [13-16].

The remaining two projects dealt with satellite-switched multiple beam systems. In one of them, we again studied protocol design and performance evaluation for integrated circuit and packet-switched systems, but the problem was considerably more complex in view of the combinatorial problems involved in

scheduling the satellite switch. Performance was studied by implementing a generalized simulator of the onboard scheduling and switching operations. Software design of the simulator was a significant task in itself due to the complexity of the system being simulated. Because of the very large computational burden involved, the simulation was implemented on a Cray computer made available to us by Bell Laboratories. Several scheduling strategies were evaluated in terms of circuit blocking and packet queueing delay. Results were reported in a recent conference paper [17], and a doctoral dissertation on this topic has just been completed. [18]

In another multibeam satellite project we studied the problem of optimally scheduling circuit and packet transmissions in systems with channelized beams of different bandwidths and systems with interference between adjacent beams. In most cases the scheduling problems were shown to be NP-complete. Several suboptimal scheduling algorithms were proposed, whose effectiveness was demonstrated by comparison with theoretical performance bounds as well as by experiments with randomly generated traffic patterns. Several publications and a doctoral thesis resulted from this work. [19-21]

5. Packet Voice

In designing and evaluating packet voice systems it is necessary to be able to predict the statistics of packet delay and possibly packet loss in order to determine whether the voice signal can be reconstructed at the destination with acceptable quality. This has been the objective of our packet voice research. A new type of queueing model in the form of an "extended" GI/G/1 queueing system was developed to accurately capture the statistical behavior of the packet voice process. The model is both analytically and computationally tractable, and provides the foundation for obtaining both insight and detailed information on system behavior. Through analysis of the model we were able to determine expressions for packet delay distributions and packet loss probabilities. These enabled us to predict the performance of a general packet voice system given its basic parameters. The results are particularly useful for systems of "medium" size too large for the

application of brute force numerical techniques, but too small to rely on simple fluid or diffusion approximations. This work has been reported in two conference papers [22, 23] and is the subject of a doctoral dissertation that was completed September 1984.

6. Decentralized Optimal Flow Control

Our recent work on optimal flow control in computer communication networks has been focused on the centralized control of a single class of users. The centralized optimal flow control for Jacksonian networks has been shown to be an isarythmic type control [27], [30], [34], [35]. Although small networks can be controlled in such a manner, the centralized approach is inefficient due to the large overhead required for obtaining the necessary information at the central controller. It is clearly desirable, therefore, to implement flow control procedures that are decentralized in nature. In this environment, users are able to execute flow control procedures based on local information only.

In our first model [29], [31] the receiving node of a given data link was assumed to accept two classes of users. The first class models the packet flow from a given source to destination. These packets are subject to flow control. The second class models the interfering traffic due to the existing resource sharing with the traffic load emanating from the other nodes of the network. The latter traffic, modeled as a continuous Poissonian flow of a fixed rate, is not directly observable. Optimal control strategies for the data link flow control protocol were obtained that maximize the total average throughput subject to a bounded total average time delay criterion from both the network and the user point of view. These strategies use partial observations: only the number of the first class of packets is available for controlling the data link. Under both optimization criteria, the resulting optimal control was shown to be a window flow control mechanism (bang-bang control). The window size L is a function of the maximum tolerated

time delay T , the input capacity c , the service rate u and the interfering flow d . It was shown that the optimal window size under the network criterion is smaller than or equal to the optimal window size under the user criterion.

The decentralized optimal flow control of a bottleneck in computer communication networks was considered in [38]. Two user classes share a high utilization link (the bottleneck) with a FCFS discipline. Each user controls its own flow using local information only. The optimal decentralized flow control which attains the global objective of maximizing the average throughput subject to a bound on the average time delay over all user classes was investigated. Under this criterion, the optimal decentralized flow control of a bottleneck is a pair of window-type mechanisms. The optimal window sizes depend on the maximum packet generation rate of the two users, c_1 and c_2 , the service rate u , and the maximum tolerable average time delay, T .

7. Optimal Flow Control of Integrated Digital Networks

The modeling of Integrated Digital Networks for optimal flow control is based on the proposed implementation of a packet switched digital overlay on the existing telephone network [32]. The model consists of a network of interconnected queues with two classes of customers (voice and data) having different priority disciplines and customer dependent routing. The voice traffic is circuit switched and the data traffic is packet switched. The voice traffic is preemptive over the data traffic at the queuing nodes. Since it has preemptive priority, the flow of class 1 customers (voice traffic) achieves the equilibrium state. Consequently, data packets are transmitted through a queuing network with random service rates (link capacities). Thus, the data traffic (class 2 customers) cannot achieve in general the equilibrium state.

The problem of data link flow control can be modeled as the control of a queuing system with random departure rate. This rate is governed by the voice traffic statistics in the system. The birth rate is chosen from the convex set of admissible controls. The general dynamic flow control problem for strategies with

partial and with complete observations was established [32]. The optimality criterion employed maximizes the average throughput subject to a system time delay constraint [24], [25], [26]. It was shown that the optimal flow control policy in the complete observation case is an adaptive window flow control mechanism [28], [32]. The window size L is a function of the maximum tolerated system time delay T , the frame duration S , the maximum data offered load c and the number of packets in the system at the beginning of the frame.

The design of the optimal data link flow control protocol with partially observed voice traffic was investigated [36]. The model employed consists of a source node that controls a queueing system with random server. The controller has only incomplete knowledge about the state of the server. A recursive optimal m.m.s.e. filter was designed to estimate the state of the voice traffic load to the controller. An adaptive window flow control mechanism with a window size chosen according to the estimated voice traffic load was implemented to control the flow of the data packets. Therefore, the optimal flow control with partial observation has been reduced to a flow control strategy with complete observations.

The class of control algorithms investigated in [37] regulates the data flow between sending and receiving user equipment and network interface units of an integrated local area network. The performance of the optimal flow control mechanisms is, in general, protocol dependent. In [37] a TDM type access protocol with movable boundary was considered. The capacity allocated to data traffic at each station is dynamically changing and depends on the ongoing traffic of the other stations. It was shown that the optimal policy is a variable window control which adapts dynamically to changes of the integrated traffic load from the other users accessing the network.

8. Fundamental Issues in Multiclass Markovian Queueing Networks

Multiclass Markovian queueing networks model computer communication network protocols in which packets are partitioned into classes. Within the same class, packets have the same queueing discipline, service time distribution and

routing assignment. These networks have also been used to model multi-tasking in computer systems. The determination of the equilibrium probabilities for multiclass Markovian queueing networks requires the solution of a set of linear equations known as the global balance equations. Unless these probabilities have a "product form", the solution to the set of balance equations is computationally unfeasible.

Our study of simple queueing systems consisting of one or two queues revealed that the topological structure of the state transition diagram is intimately connected with the product form of the equilibrium probabilities. Consequently, a geometric interpretation of the state transition diagram and its associated global balance equations in higher dimensions was pursued. The state transition diagram of an arbitrary Markovian queueing network can be decomposed into certain basic geometric shapes (building blocks). Taking these blocks in isolation a set of simple global balance equations can be written. These equations represent, for the original system, a possible set of partial balance equations. Geometrically, the original state transition diagram can be reconstructed by pasting the building blocks together. Algebraically, this procedure corresponds to a summation of the partial balance equations resulting in the set of global balance equations. There is no guarantee, however, that by following the approach delineated above the partial balance equations are consistent, i.e., have a solution. Necessary and sufficient condition for consistency were given in [4].

An extension of the results of [4] concerning the existence of product form equilibrium probabilities for multiclass Markovian queueing networks was given in [39], [40]. It was shown that the geometric replication [4] of k-cells can be applied to the class of networks consisting of queueing systems that do not make a distinction between the exact ordering of the packets at the nodes of the queueing network. These are the type I networks. PS and IS queueing systems are typical examples of type I networks. For the class of networks studied by Kelly and BCMP for which a distinction between the packet orderings is made at a queueing node a natural extension of the methods of [4] was devised. These form the type II networks. A queueing system with a LCFS/PR queueing discipline is an example of

a type II network. The basic building blocks (cells) for this case were derived. All networks studied are characterized by blocking, different queuing and service time disciplines and state dependent routing.

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